SCRREEN2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211.

Start date: 2020-11-01 Duration: 36 Months

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

KAOLIN

AUTHOR(S):

TABLE DES MATIÈRES

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KAOLIN

OVERVIEW

Kaolin is a general term encompassing clay materials rich in kaolinite group minerals (>50%wt) derived primarily from the alteration of feldspars and micas. The name kaolin is derived from the Chinese word "kaoling" meaning high ridge, the name of a hill in China, where it was mined since centuries. It is a white, soft, plastic clay mainly composed of fine-grained, plate-like particles, pertai ning mainly to kaolinite group minerals: kaolinite, dickite, nacrite, and halloysite (Murray, 2006,Pruett, 2006; McCuistion, 2006). For sake of clarity, here "kaolinitic clays" will be used as a general term, including two different raw materials: "kaolin" and "plastic clay" that come from diverse geological sources and have distinct properties and uses.

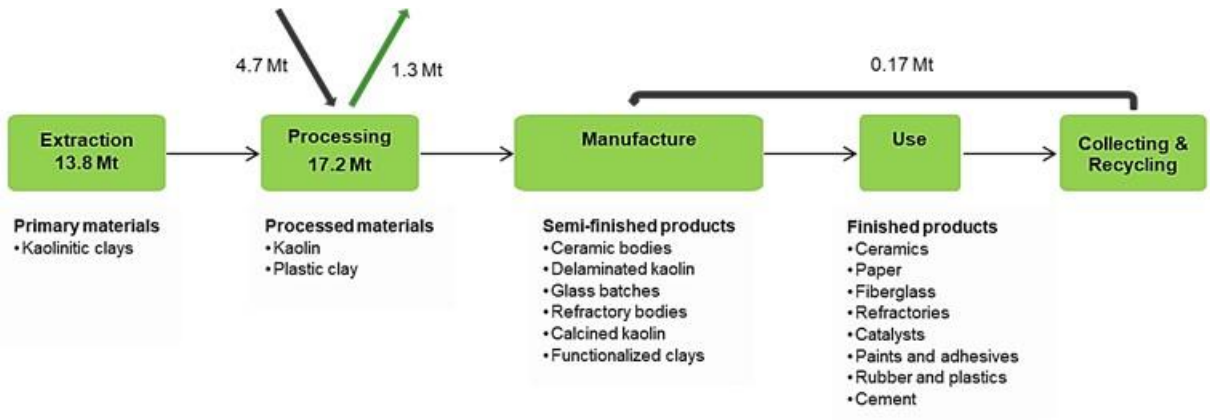

Figure 1. Simplified value chain for RM in the EU[1]

Table 1. Kaolin supply and demand (extraction) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
28 462 428	Ukraine 24% China 18% Turkey 15% India 14% Germany 10% France 7% Spain 4%	11 091 658	39%	Ukraine 78% UK 8% Turkey 4%	36%

[1] JRC elaboration on multiple sources (see next sections)

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Table 2. Kaolin supply and demand (processing) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
16 712 694	USA 31% India 26% China 19% Brazil 9% Germany 4%	3 513 064	21%	Brazil 47% UK 20% USA 20% Ukraine 13%	46%

Prices: Overall, the price of kaolin has grown consistently from 110 USD/t to 160 USD/t in past two decades. There has been little to no volatility in the market price and currently they appear to be stable for the last two years.

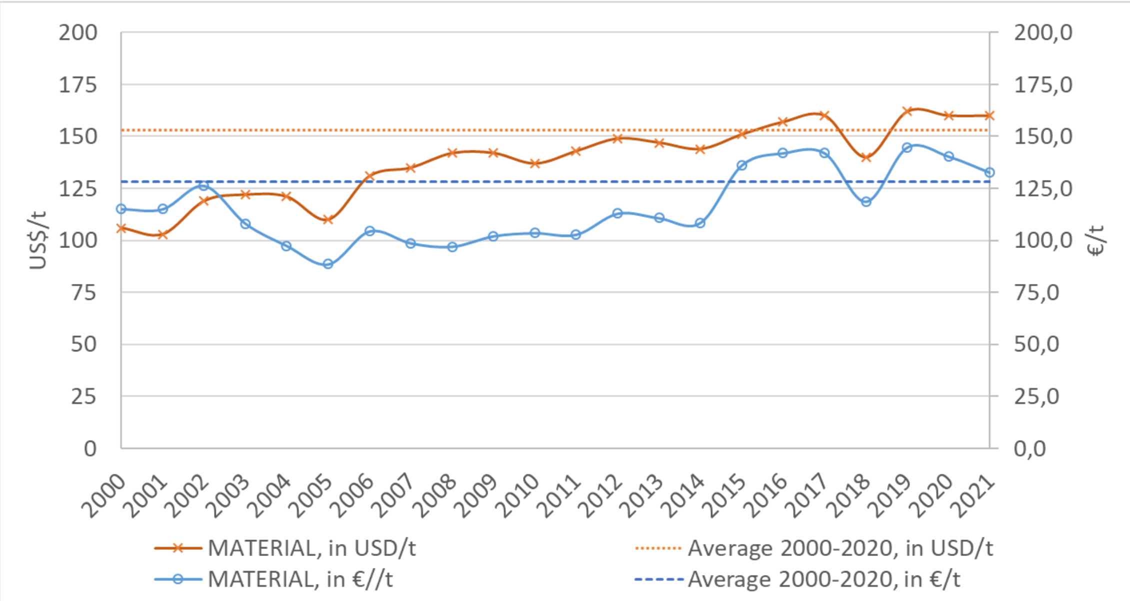

Figure 2. Annual average price of RM between 2000 and 2020 (USGS, 2021)[2].

Primary supply:

Secondary supply:

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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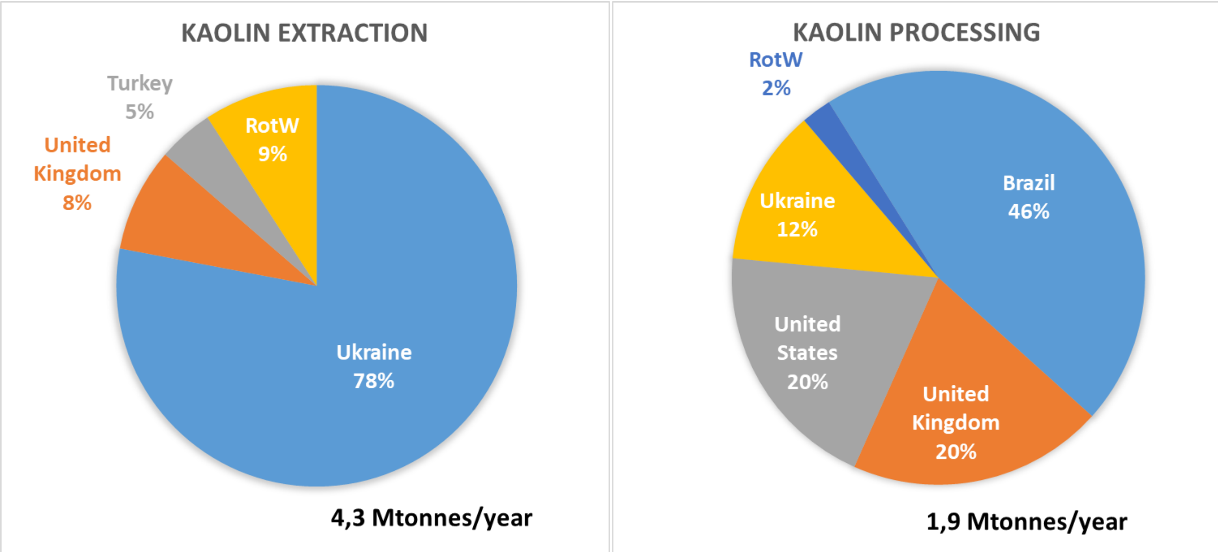

Figure 3. EU sourcing of kaolin and global mine production (2016-2020)

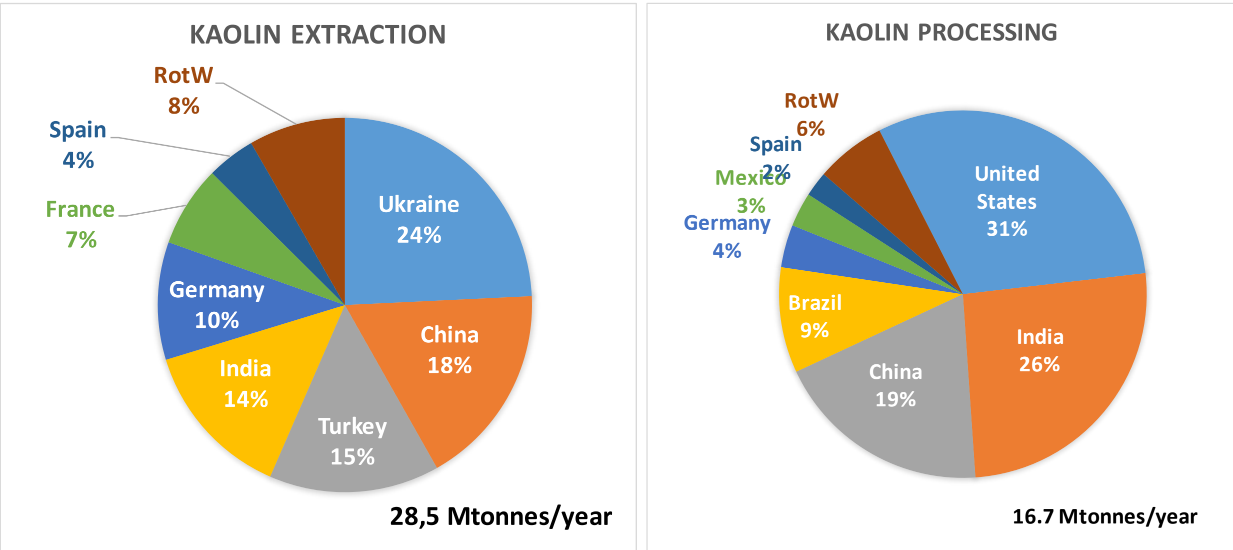

Figure 4. Global mine production (2016-2020)

Uses: The main industrial applications of kaolinitic clays are in the manufacture of ceramics, paper, fiberglass, refractories, catalysts, and paints. Minor volumes are used in the rubber, plastics, adhesives, and cement industries, along with a number of further end-users (insecticides, cosmetics, sealants, pharmaceuticals, fertilizers, etc.). Plastic clays mainly find application in ceramics and refractories, even if they can replace kaolin in most uses (USGS, 2018).

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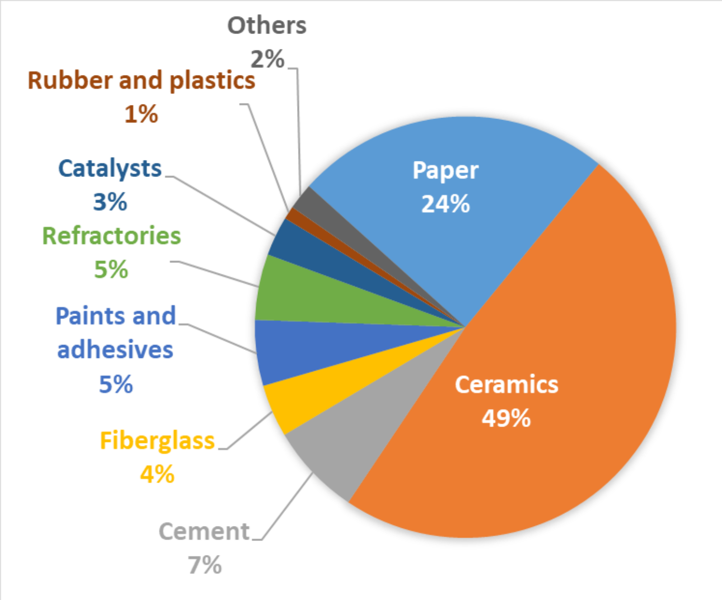

Figure 5: EU uses of RM

Substitution: Kaolinitic clays have a wide spectrum of applications, each having its own alternatives for kaolin or plastic clay (European Commission, 2017b; Kogel, 2006; USGS, 2018).

Table 3. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Paper	40%	Talc	7%	Similar or lower costs	Similar
	40%	Calcium carbonate (GCC or PCC)	30%	Similar or lower costs	Similar
	40%	Zeolites	1%	Similar or lower costs	Reduced
	40%	Diatomite	1%	Similar or lower costs	Reduced
Ceramics	20%	Pyrophyllite	1%	Similar or lower costs	Similar
Cement	11%	Alumina	2%	Similar or lower costs	Similar
	11%	Bauxite	8%	Similar or lower costs	Similar
Fiberglass	7%	Feldspar	10%	Similar or lower costs	Similar
Paints and adhesives	7%	Lime (calcium carbonate)	5%	Similar or lower costs	Similar
	7%	Talc	5%	Slightly higher costs	Similar
	7%	Wollastonite	2%	Slightly higher costs	Similar
	7%	Feldspar	2%	Slightly higher costs	Similar
	7%	Mica	2%	Slightly higher costs	Similar
	7%	Pyrophyllite	1%	Similar or lower costs	Reduced
	7%	Silica	1%	Similar or lower costs	Reduced
	7%	Diatomite	1%	Similar or lower costs	Reduced
	7%	Bentonite	1%	Slightly higher costs	Reduced
Refractories	5%	Fireclay	10%	Similar or lower costs	Reduced
	5%	Pyrophyllite	5%	Similar or lower costs	Reduced
Catalysts	5%	Zeolites	20%	Slightly higher costs	Similar
	5%	Rare earth oxides	5%	Very high costs	Similar

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	5%	Silica	2%	Similar or lower costs	Reduced
	5%	Alumina	2%	Similar or lower costs	Reduced
	5%	Bauxite	1%	Similar or lower costs	Reduced
Rubber and plastics	2%	Lime (calcium carbonate)	5%	Similar or lower costs	Similar
	2%	Talc	5%	Slightly higher costs	Similar
	2%	Wollastonite	2%	Very high costs	Similar
	2%	Feldspar	2%	Slightly higher costs	Similar
	2%	Mica	2%	Slightly higher costs	Similar
	2%	Pyrophyllite	1%	Similar or lower costs	Reduced
	2%	Silica	1%	Similar or lower costs	Reduced
	2%	Diatomite	1%	Similar or lower costs	Reduced
	2%	Bentonite	1%	Slightly higher costs	Reduced

Other issues: The International Agency for Research on Cancer (2012) includes the dust of crystalline silica, the main component of kaolin, in Group 1, since it is "carcinogenic to humans". The Classification, Packaging and Labelling EU Regulation (2008) categorises another component of kaolin, titanium dioxide (TiO_2), as carcinogenic level 2, given that it is "suspected of causing cancer". Furthermore, the International Agency for Research on Cancer (2022) inserted TiO_2 in Group 2B, stating that it is "possibly carcinogenic". Kaolin is extensively used in cosmetics and dermal exposure to this substance doesn't pose a significant threat to humans (World Health Organization, 2005). By contrast, more recent studies such as (Kawanishi, M. et al., 2020) show that "fine particles of kaolin tended to have higher genotoxic potency [over human epidermal keratinocytes and dermal fibroblasts] than coarse particles". According to the (World Health Organization, 2005) kaolin has low toxicity to aquatic species and its mining doesn't pose any significant toxicological danger to the environment.

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MARKET ANALYSIS, TRADE AND PRICES

In this assessment, the term "kaolin clay" is used for kaolin, kaolinic clay, fireclays and clays. (SCRREEN2 workshop, 2022).

To differentiate the extraction stage from the processing stage, raw kaolin will refer to the extraction of kaolin, while beneficiated kaolin will refer to its processing. (SCRREEN2 workshop, 2022).

When looking at World Mining Data (WMD 2022) and the reported production of kaolin, it appears that such data combine extraction and processing stages. For the criticality assessment, a specific set of data was built to split extraction and processing over 2016-2020. These are the data reported in Table 4 and Table 5.

Such raw materials go on the market with a plethora of names: kaolin (raw and calcined), ball clay, China clay, kaolinitic clay, plastic clay, kaolinitic earth, refractory clay, fireclay, halloysite, and so on. Every name should correspond to specific features, but there are no generally accepted definitions (Pruett, 2006; McCuistion, 2006). Thus, commercial terms reflect more the customs in each sector than actual requirements about composition or technological properties.

Commercial kaolinitic clays often do not entirely fulfil the above definition: the colour can vary from white to light brown; both 'soft' and 'hard' (i.e., lithified) kaolins are well-known; plasticity and particle size distribution can vary widely; along with kaolinite, other phases are usually present: quartz, feldspars, and other phyllosilicates (illite, smectite, and mixed layers) are the most common.

GLOBAL MARKET

Table 4. Kaolin supply and demand (extraction) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
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The world annual production of raw kaolin is about 28.5 million tonnes (average 2016-2020). Around 16.7 million tonnes of beneficiated kaolin are produced globally. Beneficiated kaolin has a 4 billion EUR (4.24 billion USD) turnover. (Grand View Research, 2022). The main players in the kaolin market are LB Minerals Ltd, BASF SE, Sibelco, KaMin LLC, Thiele Kaolin Company, Imerys S.A., I-Minerals Inc., Quazwerke GmbH, Maoming Xingli, Kaolin Co. Ltd and EICL Ltd.

Kaolin is used as filler and coating in paper (40%); as plasticity provider in ceramic bodies (20%); as filler and extender in paints and adhesives (7%); as alumina source in fiberglass (7%), and as support for catalysts (5%); and in rubber and plastics (2%) (SCRREEN2 workshop, 2022).

The kaolin market is estimated to grow from 2022 to 2030 at a compound annual growth rate of 3.7%, reaching 5.52 billion euros (USD 5.87 billion) by 2030 (Grand View Research, 2022).

Kaolin demand is driven by ceramics, paints and coatings used in construction. The growth in building & construction will be driven by diverse government schemes and subsidies to increase housing supply. Ceramics revenue is estimated to grow at a Compound Annual Growth Rate of 5.2% (Grand View Research, 2022).

Kaolin's use in the paper industry will be driven by the expansion of paper industry in Asia Pacific and South America (Grand View Research, 2022).

The Covid-19 pandemic impacted product demand in 2020 and led to an adjusted industry growth rate (Grand View Research, 2022).

EU TRADE

For this assessment, Kaolin is evaluated at extraction and processing stages.

Table 6. Relevant Eurostat CN trade codes for Kaolin

Extraction		Processing	
CN trade code	**title**	**CN trade code**	**title**
25070080 **25083000** **25084000**	Kaolinitic clay Fireclay Clay	**25070020**	Kaolin

EU import of kaolinitic clay has increased since 2009 followed by a decline after 2017 reaching a low of 1.5 million tonnes in 2020. On the contrary, Exports have remained steadily low throughout with maximum volume close to 0.4 million tonnes in 2019. Post 2019 there has been a decline in the export volume.

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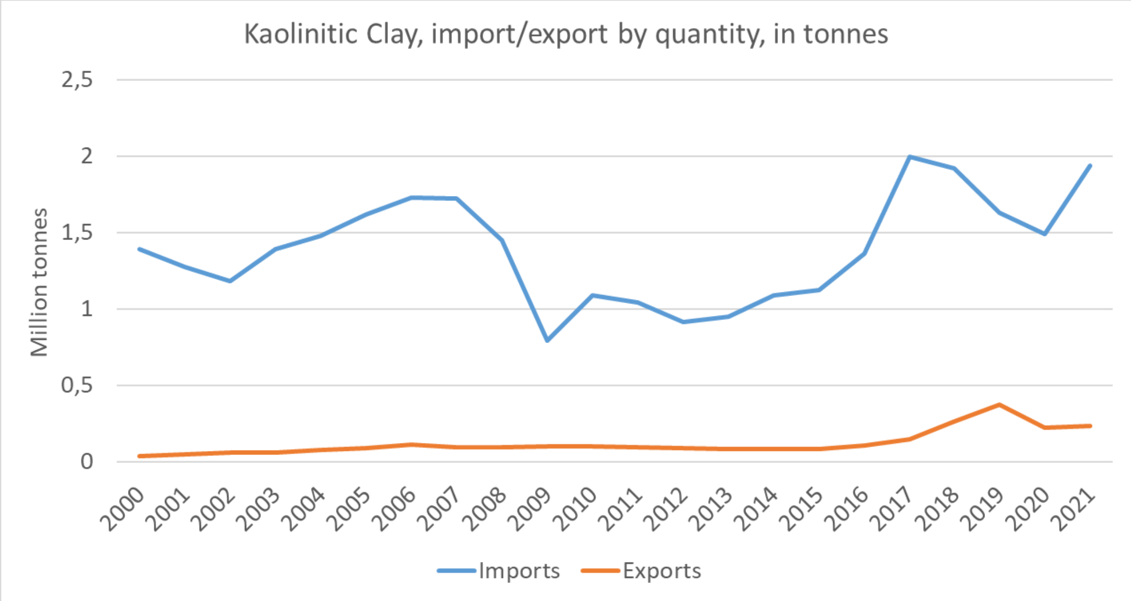

Figure 6. EU imports of kaolinitic clay (CN 25070080) by country from 2000 to 2021 (Eurostat, 2022)

Ukraine has been the largest supplier of Kaolinitic Clay for the EU followed by UK. The contribution of Ukraine as a supplier of kaolinitic clay has increased with time. UK's proportion in the import mix, on the other hand, has reduced with time.

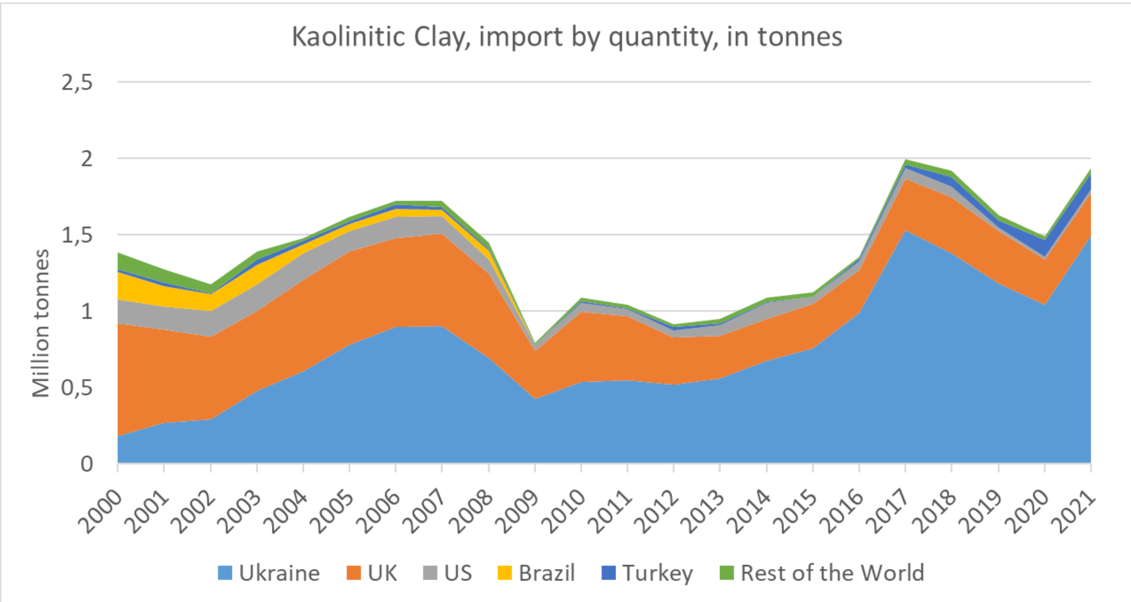

Figure 7. EU imports of kaolinitic clay (CN 25070080) by country from 2000 to 2021 (Eurostat, 2022)

EU imports of fireclay have increased gradually in the last decade reaching almost 2 million tonnes in 2021. On the other hand, the exports have been almost non-existent since 2000.

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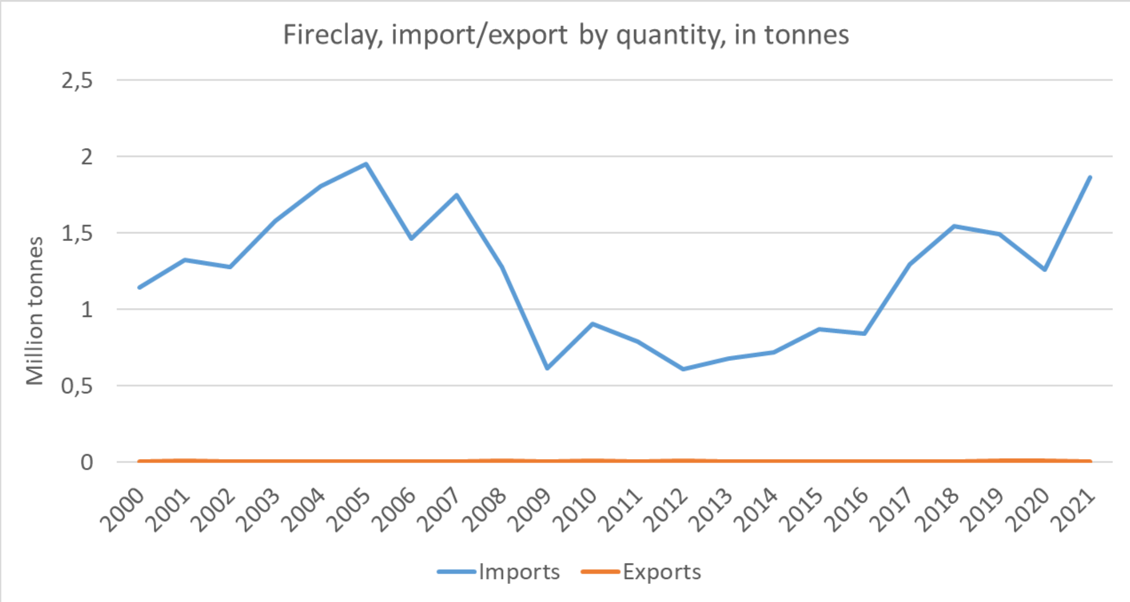

Figure 8. EU imports of fireclay (CN 25083000) by country from 2000 to 2021 (Eurostat, 2022)

Majority of Fireclay in the EU is imported by Ukraine. The numbers have increased over last decade reaching a quantity of 1.5 million tonnes last year.

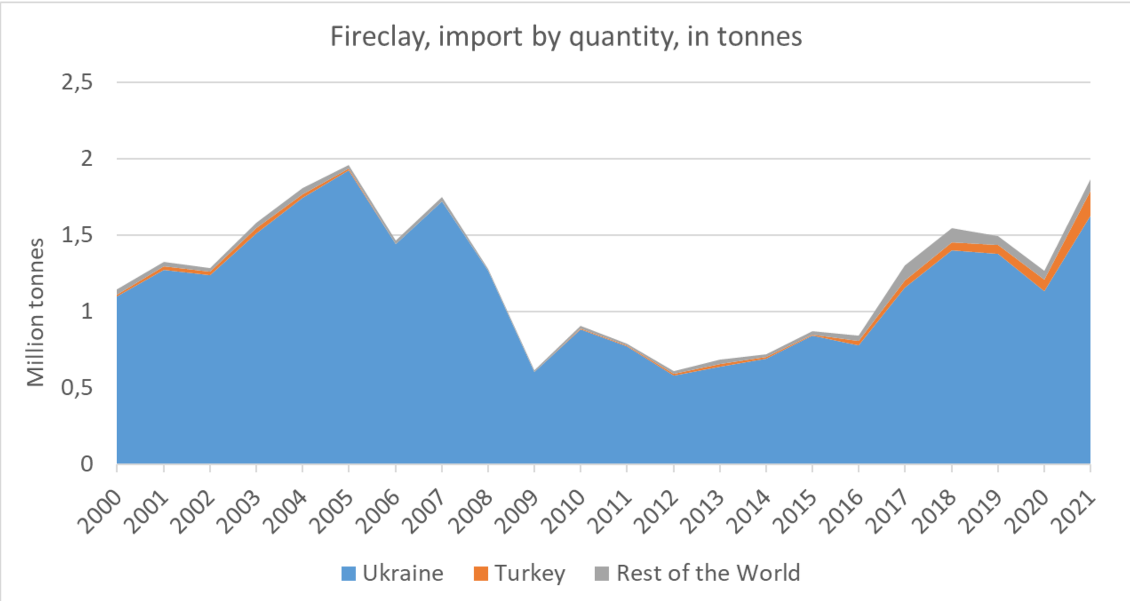

Figure 9. EU imports of fireclay (CN 25083000) by country from 2000 to 2021 (Eurostat, 2022)

Clay imported by the EU has shown vast fluctuations over the last 20 years with numerous highs and lows. Imports have gone down after 2017 but have picked up in quantity last year. Exports have been consistently low comparatively close to 0.2 million tonnes in the last 5 years.

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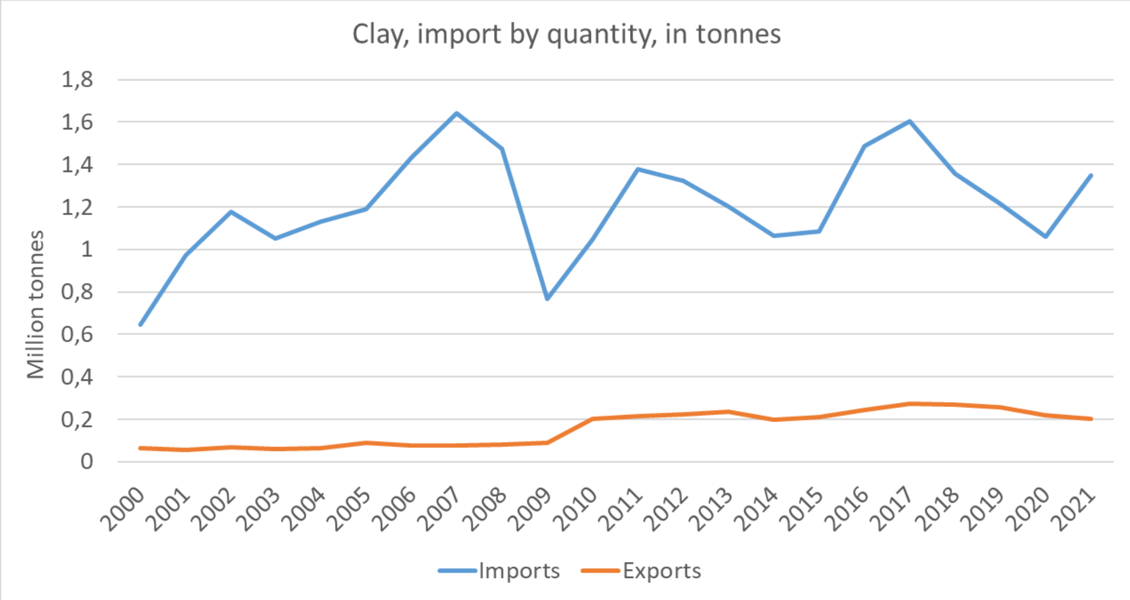

Figure 10. EU imports of clay (CN 25084000) by country from 2000 to 2021 (Eurostat, 2022)

Majority of the clay imported by the EU comes from Ukraine. However, since 2017 these numbers have declined a lot hitting a low of 0.5 million tonnes in 2020. A small proportion is also imported from Turkey, Senegal and Serbia.

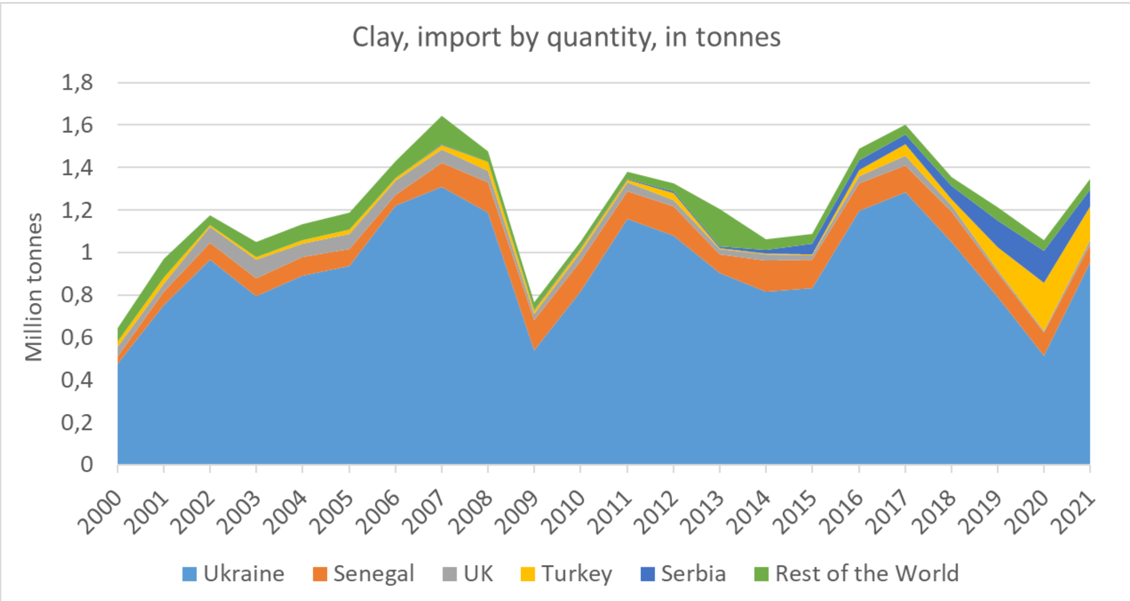

Figure 11. EU imports of clay (CN 25084000) by country from 2000 to 2021 (Eurostat, 2022)

EU imports for kaolin have declined rapidly in the last decade. On the other hand, exports have been the same throughout with a slight increase in the last year. There is still a huge gap between imports and exports by 1 million tonnes in 2021.

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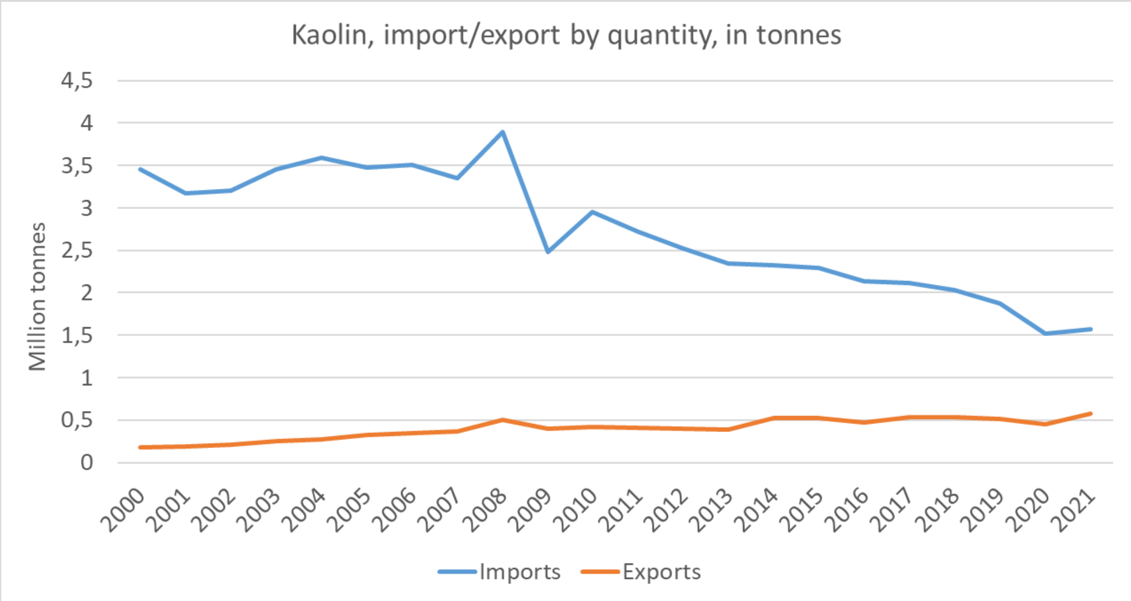

Figure 12. EU trade flows of kaolin (CN 25070020) from 2000 to 2021 (Eurostat, 2022)

Overall, contributions from all the source countries have declined gradually over the last 10 years post financial crisis. Brazil is the largest contributor followed by US, Ukraine and UK.

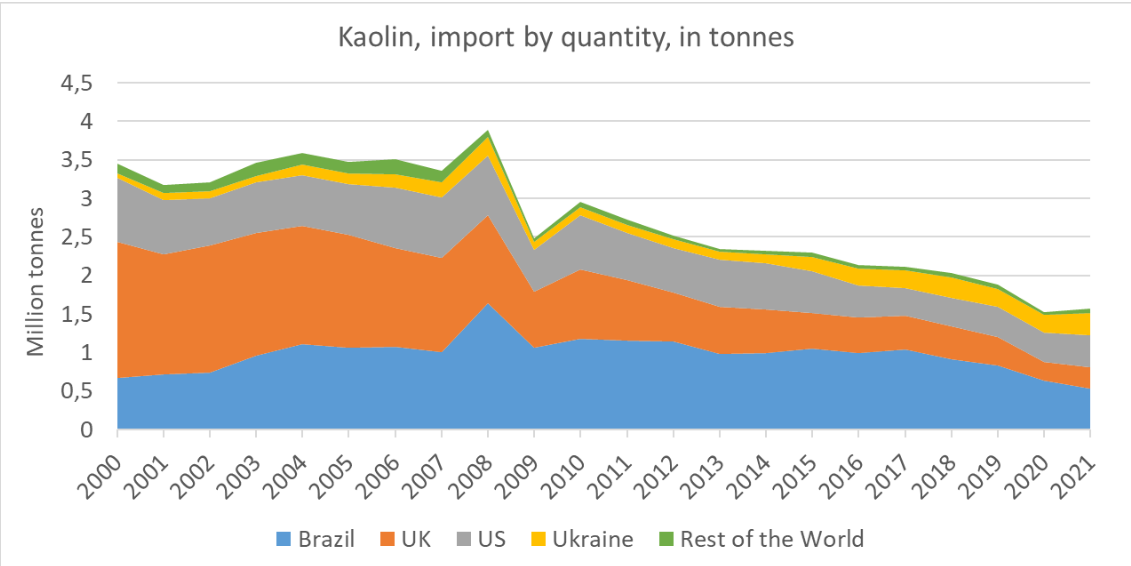

Figure 13. EU trade flows of kaolin (CN 25070020) from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

Overall, the price of kaolin has grown consistently from 110 USD/t to 160 USD/t in past two decades. There has been little to no volatility in the market price and currently they appear to be stable for the last two years.

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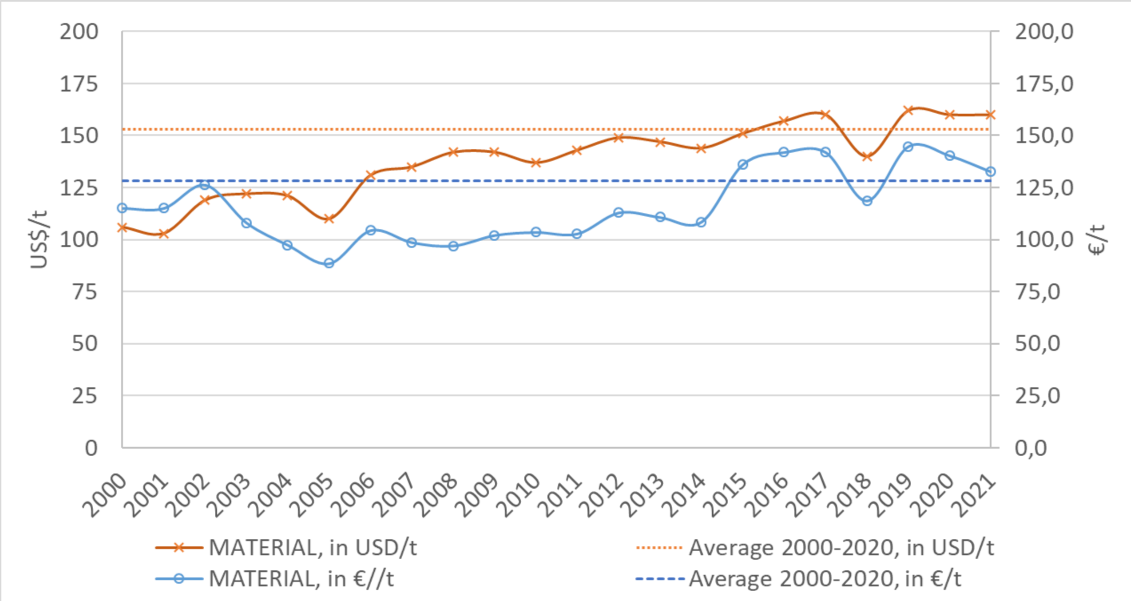

Figure 14. Annual average price of Kaolin between 2000 and 2021, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2021 (USGS, 2022)

KAOLIN DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Kaolinitic clay EU consumption is assessed at extraction and processing stages. Kaolinitic clay extraction stage EU consumption is presented by HS code CN 25083000 - Fireclay (excl. kaolin and other kaolinic clays and expanded clay), CN 25084000 - Clays (excl. fireclay, bentonite, kaolin and other kaolinic clays and expanded clay) and CN 25070080 - Kaolinic clays (other than kaolin). Kaolin processing stage EU consumption is presented by CN 25070020 - Kaolin.

Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from several sources including WMD (2022), BGR (2022), Dondi (2022), Czech Geological survey (2022), Polish Geological Institute (2022), DGEG (2022), EME (2022) and BRGM (2020) allowing a split between extraction and processing stages over the 2016-2020 period of time.

[3] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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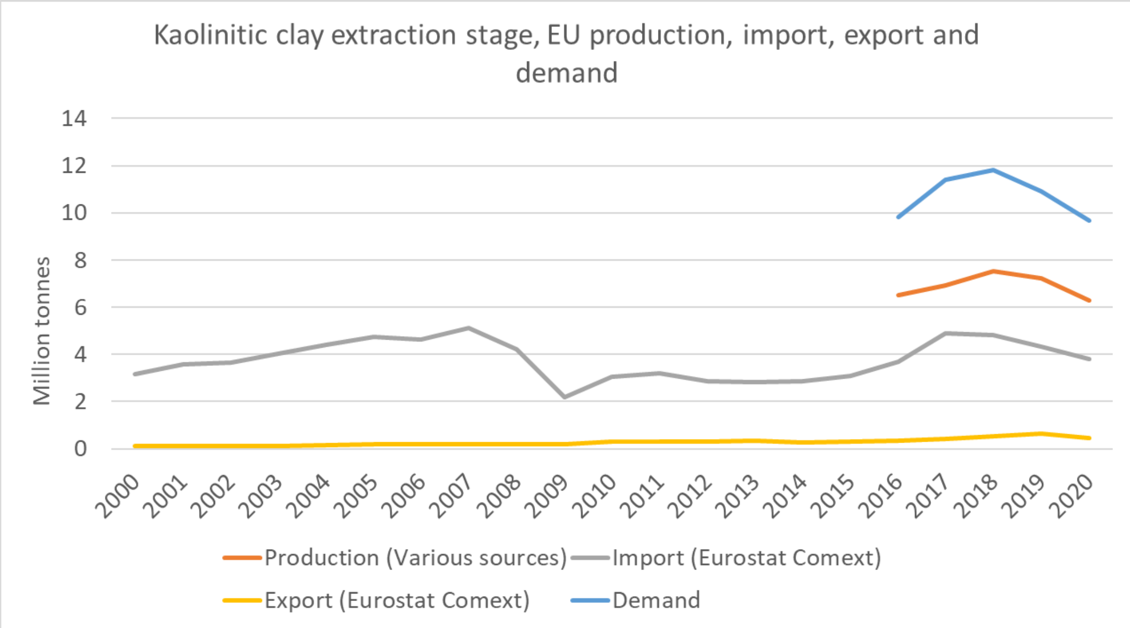

Figure 15. Kaolinitic clay (CN 25083000, CN 25084000, CN 25070080) extraction stage apparent EU consumption. Production data is available from various sources listed above (EU production+import-export).

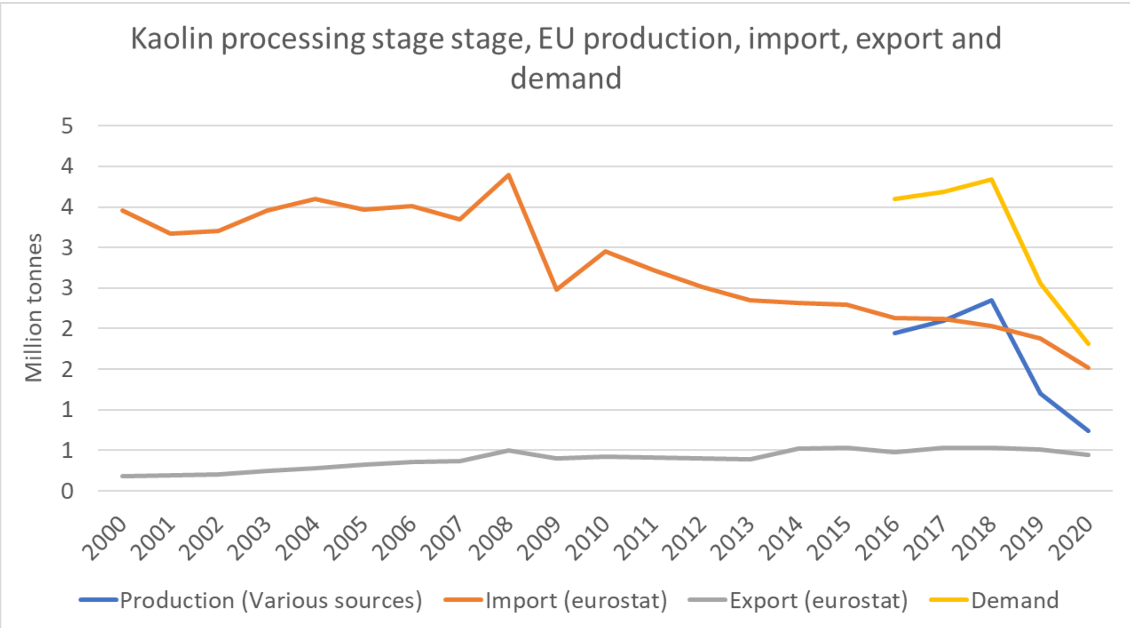

Figure 16. Kaolin (CN 25070020) processing stage apparent EU consumption. Production data is available from various sources listed above (EU production+import-export).

Average import reliance of kaolinitic clay at extraction stage is 23.2 % for 2016-2020.

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GLOBAL AND EU USES AND END-USES

The main industrial applications of kaolinitic clays are in the manufacture of ceramics, paper, fiberglass, refractories, catalysts, and paints. Minor volumes are used in the rubber, plastics, adhesives, and cement industries, along with a number of further end-users (insecticides, cosmetics, sealants, pharmaceuticals, fertilizers, etc.). Plastic clays mainly find application in ceramics and refractories, even if they can replace kaolin in most uses (USGS, 2018).

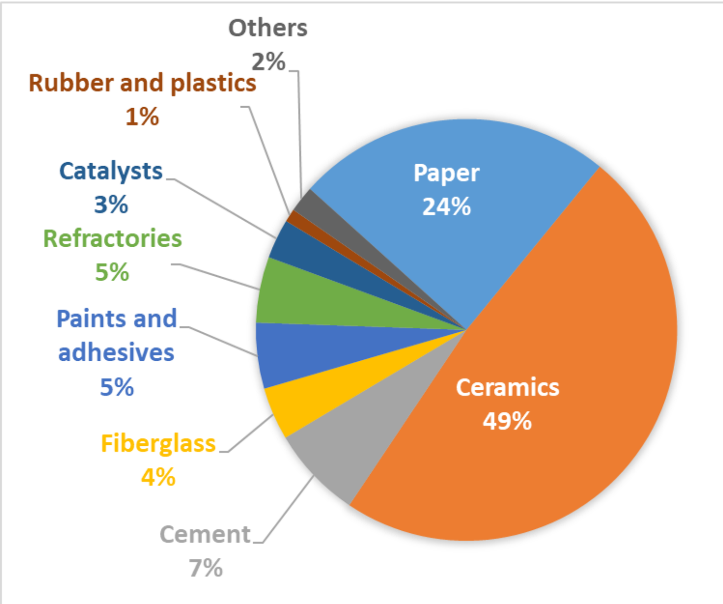

Figure 17. End uses of kaolinitic clays, average 2012-2016, (SCRREEN expert workshops, 2022)

Table 7. Kaolin applications (IMA-Europe, 2018a), 2-digit NACE sectors and value added per sector, 2019 (Eurostat 2022)

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Ceramics	C23 - Manufacture of other non-metallic mineral products	69,888.20	23.31, 23.42, 23.41, 23.4
Paper	C17 - Manufacture of paper and paper products	47,266.00	17.1
Fiberglass	C23 - Manufacture of other non-metallic mineral products	69,888.20	23.14
Refractories	C23 - Manufacture of other non-metallic mineral products	69,888.20	23.2
Catalysts	C19 - Manufacture of coke and refined petroleum products	25,475.50	19.2
Paints and adhesives	C20 - Manufacture of chemicals and chemical products	117,093.2	20.30, 20.52
Rubber and plastics	C22 - Manufacture of rubber and plastic products	92,673.50	22.10, 22.20
Cement	C23 - Manufacture of other non-metallic mineral products	69,888.20	23.51

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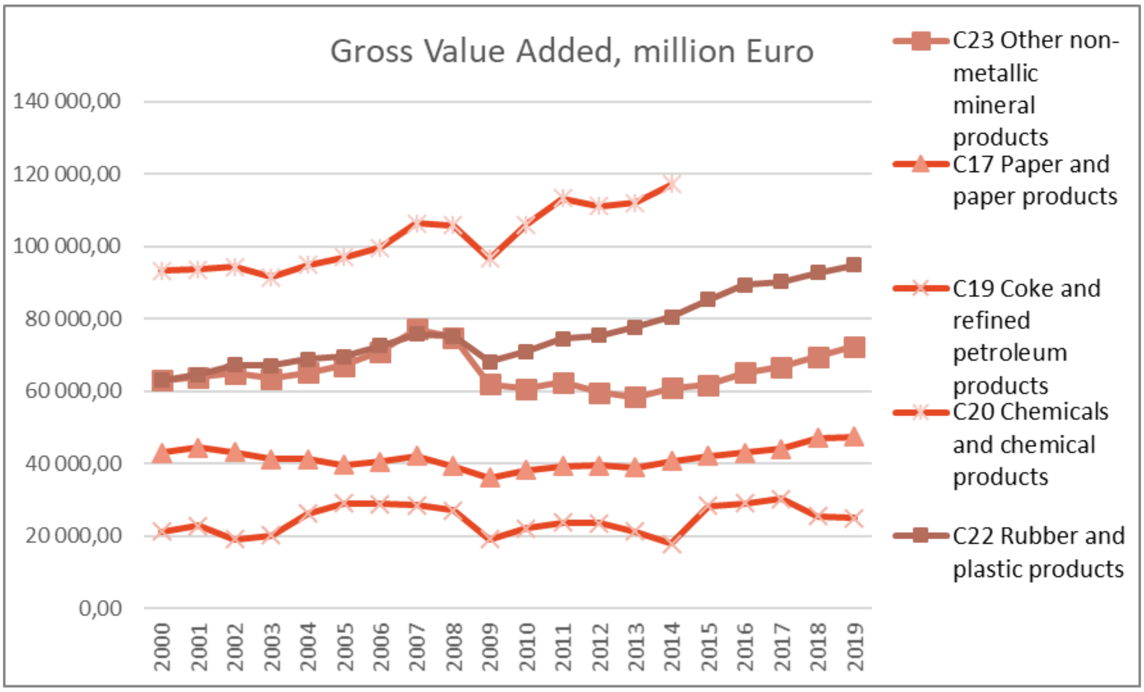

Figure 18. Value added per 2-digit NACE sector over time (Eurostat, 2022)

CERAMICS

Ane extensive range of kaolin products is produced to meet the requirements the ceramics industry.

It is used in traditional ceramics (whiteware, sanitaryware and tiles), structural clay products, advanced ceramics and catalyst supports.

Kaolins and ball clays, which are kaolinitic clays, are both used as major ingredients in many ceramic products. (Murray, 2006; Pruett, 2006; McCuistion, 2006, Dondi, 2014; European Commission, 2017b)

PAPER

The most important industrial use of kaolin as a filler mineral is in the paper industry where it is used in both filler and coating applications.

Water washed kaolin is the preferred type of kaolin for paper filling applications, as it is readily dispersible in water.

Air floated kaolin tends to be used in less expensive paper products (as it generally has a lower brightness than water washed grades). .

FIBREGLASS

Kaolin is a major component used in the production of fiberglass.

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Fiberglass has a large number of applications, including insulation, reinforcement of plastics, textile yarn, electronic circuit board substrates, paper, cloth, and roofing shingles.

The basic component materials used to make fiberglass are silica, kaolin, and limestone, along with small amounts of boric acid, soda ash, and sodium sulfate.

REFRACTORIES

Kaolin is one of a number of alumino-silicate clays consumed by the refractory industry. These clays have alumina (Al2O3) contents of around 20% up to 45.9% for theoretically pure kaolin. In general terms, the higher the alumina content the more refractory the material.

CATALYSTS

The most important mineral used in the manufacture of carriers for catalysts is kaolin.

The largest use of kaolin is in catalyst substrates in the catalytic cracking of petroleum.

Because many catalysts are used at high temperatures and pressures, the refractory character of kaolin is appropriate for these applications. (Murray, H. H. ,1961).

PAINTS & ADHESIVES

Kaolin is used as a filler to improve a variety of processing characteristics in adhesives in addition to reinforcement and thixotropy.

RUBBER & PLASTICS

Kaolin is used as a filler in plastics. It helps to produce a smooth surface finish, reduces cracking and shrinkage during curing, obscures the fibre pattern when fiberglass is used as reinforcement, improves thermal stability, contributes to a high impact strength, improves resistance to chemical action and weathering, and helps control flow properties.

CEMENT

Cement is made by mixing materials containing lime, silica, alumina, and iron oxide. This mixture is sintered and then pulverized at which time a retardant, gypsum is added. Kaolin is an ideal source of alumina and silica and also makes the cement whiter.

Pozzolanic materials have long been used in the cement industry. The majority of these materials are co-products from other industries, such as coal fly ash, blast furnace slag or fumed silica.

Metakaolin, produced by calcining kaolin at 650-800°C, is a highly reactive pozzolan suitable for use as a cementing material in concrete. Metakaolin particles are nearly ten times smaller than cement particles,

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which allows the production of a denser, more impervious concrete. The use of metakaolin in concrete increases durability and also improves mechanical properties. (Murray, H. H. ,1961).

SUBSTITUTION

Table 8. Main uses and potential substitution

Use	Share*	Substitutes	Sub share	Cost	Performance
Paper	40%	Talc	7%	Similar or lower costs	Similar
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Rubber and plastics	2%	Lime (calcium carbonate)	5%	Similar or lower costs	Similar
	2%	Talc	5%	Slightly higher costs	Similar
	2%	Wollastonite	2%	Very high costs	Similar
	2%	Feldspar	2%	Slightly higher costs	Similar
	2%	Mica	2%	Slightly higher costs	Similar
	2%	Pyrophyllite	1%	Similar or lower costs	Reduced
	2%	Silica	1%	Similar or lower costs	Reduced
	2%	Diatomite	1%	Similar or lower costs	Reduced
	2%	Bentonite	1%	Slightly higher costs	Reduced

* EU end use shares for kaolin, adapted for kaolin and plastic clays (Dondi, 2014; IMA-Europe, 2018a).

Kaolinitic clays have a wide spectrum of applications, each having its own alternatives for kaolin or plastic clay (European Commission, 2017b; Kogel, 2006; USGS, 2018).

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In **ceramics**, a typical substitute is pyrophyllite (Dondi, 2014).

In the production of **paper**, the main substitutes of kaolin are talc, calcium carbonate (ground or precipitated), zeolites, diatomite, or gypsum. Ffeldspar could replace kaolin in the manufacture of **fibreglass**.

In r**efractories**, kaolinitic clays can be replaced by fireclay or pyrophyllite.

For **catalysts**, alternatives to kaolin can be found in zeolites, rare earth oxides, silica, alumina, or bauxite.

In **paints and adhesives**, kaolin can be substituted by calcium carbonate, talc, wollastonite, feldspar, mica, pyrophyllite, silica, diatomite, or bentonite.

As a **filler in rubber and plastics**, kaolin can be replaced by calcium carbonate, talc, wollastonite, feldspar, mica, pyrophyllite, silica, diatomite, bentonite.

In **cement**, substitutes can be alumina or bauxite.

SUPPLY

EU SUPPLY CHAIN

The average annual EU extraction of raw kaolin and kaolinic clays in the period 2016-2022 was 10 Mt according WMD (WMD, 2022) but only 8.6 Mt according the various sources used in the criticality assessment and by combining extraction and processing stage. The EU average annual exports of various kaolin and kaolinic clays products was 1 Mt over the same period. The EU demand is also partially covered by importing primarily from Ukraine, Brazil and the United Kingdom. The recycling rate if kaolin is very low, not exceeding 1%. Figure 1 shows extracted amount of kaolin and kaolinitic clays by the major EU producers in 2020 (Eurostat, 2021).

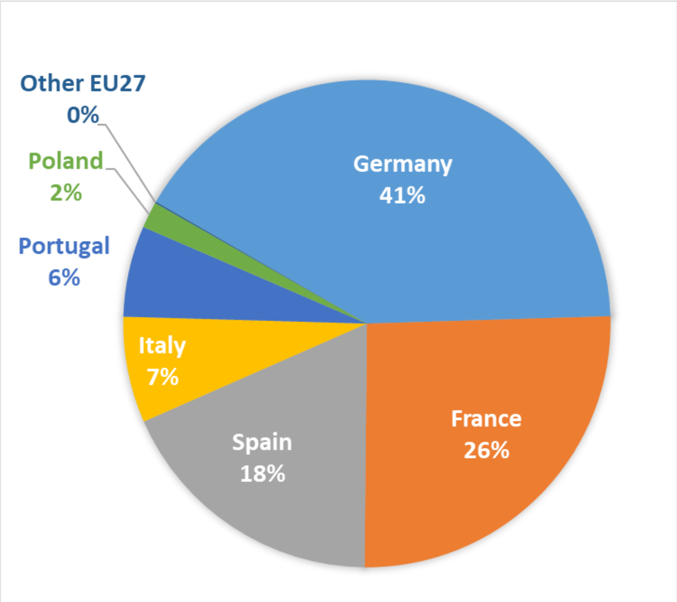

Figure 19. kaolin and kaolinitic clays production in EU27 over 2016-2020 (Criticality assessment sources).

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF KAOLINITIC CLAYS

GEOLOGICAL OCCURRENCE

Deposits of kaolinitic clays, in all sizes, can be found all over the world (Murray, 2006,Pruett, 2006; McCuistion, 2006). Kaolinitic clays may occur as primary or secondary ore, where the primary type is quintessentially kaolin, originated by alteration of igneous or metamorphic rocks for action of hydrothermal fluids or weathering. The secondary type, typically plastic clays, is sedimentary and formed through erosion, transportation and deposition of mineral particles. Kaolin is formed by alteration of feldspar-rich rocks, like granite or rhyolite, through weathering or hydrothermal processes. The process which converted the parent rock into the soft matrix found in kaolin pits is known as "kaolinisation" (Murray, 2006; Pruett, 2006). Some primary minerals (e.g., quartz, anatase) remain substantially unaffected, whilst feldspars are transformed into kaolinite group minerals (the most common being kaolinite and halloysite) and sometimes other phyllosilicates (illite, smectite, mixed layers).

GLOBAL RESOURCES AND RESERVES

Kaolinisation is a common process by which a wide range of feldspathic rocks can be transformed, through weathering or hydrothermal action, into a product with a variable degree of alteration (hence different kaolinite content). On this basis, resources of kaolinitic clays are considered extremely large and widespread. In reality, there are many technological constraints in the various industrial applications that significantly restrict the resources actually useful for end-users (Pruett, 2006; McCuistion, 2006; Dondi, 2014). This is crucial for plastic clays, which reserves appear to be not so extended as previously thought, at variance of kaolin, which can be beneficiated by mineralurgical treatments. Major kaolin reserves are located in the United States (Georgia), Australia, Brazil (Jari, Capim), Germany (Bavaria, Saxony), the UK (Cornwall, Devon), Czechia (Karlovy Vary, Pilsen), France (Bretagne), Ukraine, Poland, China and India (Table 1).

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of kaolin and plastic clays in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not make accessible data on reserves. Individual companies may publish mineral resource and reserve reports, but by a variety of systems of reporting, often depending on the location of their operation, their corporate identity and stock market requirements. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

The recent exploitation of the world-class kaolin deposit in Wickepin, Australia should be stressed out. The deposit occurs 220km south-east of Perth and was discovered and drilled out by Rio Tinto in 1999. It consists of an in-situ primary kaolin deposit with high brightness and low impurities suitable for all kaolin market applications. The owner company (WAK) estimates an amount of 30.5 Mt of kaolinised granite in its mining lease which delivers a 31-year life of mine (LoM). It has also access to 644.5 Mt of kaolin resources which can extend LoM (WA Kaolin, 2020). The mining and beneficiation activities began in 2022 (WA Kaolin, 2022).

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A second large mining project is expected to begin in Australia during 2023-2024. Great White Kaolin Project (GWKP) aims to the extraction of world-class kaolin/halloysite. The project located on South Australia's Eyre Peninsula. The proved kaolin amount is estimated at 5.2 Mt, while the probable at 9.9 Mt (ATIC, 2022).

Table 9. Global reserves of kaolininitic clays (Minerals4EU, 2019)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Czechia	National reporting code	225.1 506.0	Mt	kaolin	Economic explored Economic prospected
Slovakia	None None	22.2 5.9	Mt	kaolin	Verified Z1 Probable Z2
Spain	none	93.8	Mt	kaolin	Proven reserves
Ukraine	Russian classification	1.6 137.9	Mt	kaolin kaolin	A B
United Kingdom	National reporting code	>50.0 52.0	Mt	kaolin ball clay	Permitted reserves Permitted reserves

EU RESOURCES AND RESERVES

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for kaolin and plastic clays. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for kaolin, but this information does not provide a complete picture for Europe (Minerals4EU, 2019). It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). Many documented resources are based on historic estimates and are of little current economic interest.

Table 10.Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2019)

Country	eporting code	Qty	Unit	Grade	Code resource type
Poland	National report. code	139.1 73.6	Mt		A+B+C1 C2+D
Czechia	National report. code	460.0 25.1	Mt		Potentially economic P1
Hungary	Russian classification	1.7	Mt	1.6 t/m^3	A+B
Slovakia	None None None	22.2 5.9 3.6	Mt		verified Z1 probable Z2 subeconomic

Known resources of kaolinitic clays exist in most EU countries, but limited quantitative data are available. The Minerals4EU database has filed 534 kaolin deposits and 82 occurrences, but this information is limited to some countries (mainly Spain, Portugal, France, and Czechia). Kaolin deposits are well known in Belgium, Bulgaria, Czechia, France, Germany, Italy, Poland, Portugal, Romania, and Spain (where mines are in operation). Limited or discontinued production is recorded also in Austria, Denmark, Finland, Greece, Hungary, Slovakia, and Sweden.

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Plastic clays are currently exploited in Austria, Czechia, France, Germany, Italy, Poland, Portugal, Romania, Slovakia, and Spain. In addition, limited or discontinued production is recorded also in Bulgaria, Croatia, and Hungary.

WORLD PRODUCTION

The annual average global production of kaolin during the period 2016-2020 is estimated at 45.6 Mt according to WMD and at 40.8 Mt according to USGS data (Figure 2,3) (WMD, since 1984; USGS, since 2000). India, China, Germany, United States and Czech Republic are the major kaolin producers (with 8 Mt, 6.5 Mt, 5 Mt, 4.6 Mt and 3 Mt production amounts, respectively in 2020) (WMD, since 1984).

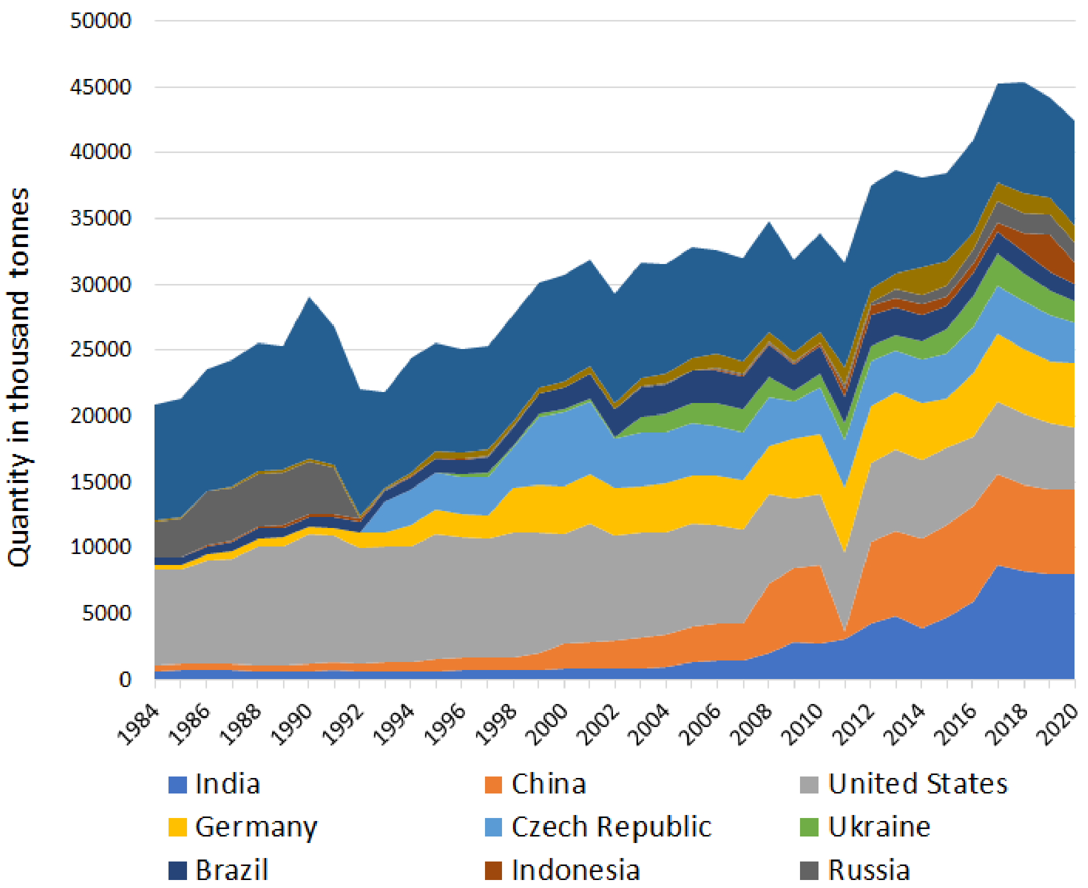

Figure 20. Global kaolin production since 1984 according to WMD (WMD, since 1984).

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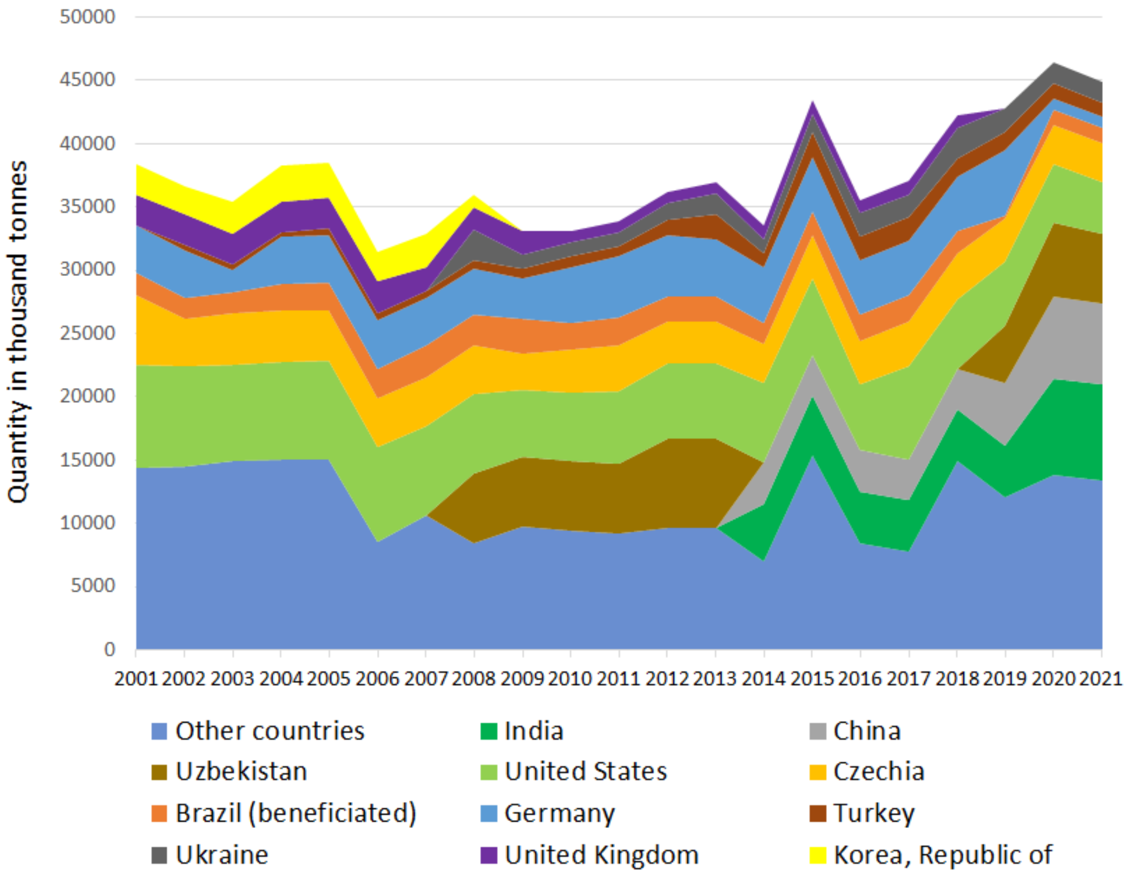

Figure 21.Global kaolin production since 2000 according to USGS (USGS, since 2000).

OUTLOOK FOR SUPPLY

The global kaolin market is estimated to growth with a rate of 3.7% until 2030 due to the growth of the paper, ceramics and fiberglass industries. The increased amount demand is expected to be covered by the production increasing in a number of producer countries among them: China, India, Vietnam, Malaysia and South Korea. Production is also expected to increase Middle East due to the ongoing expansion of the construction industry in the region (WA Kaolin, 2022b).

SUPPLY FROM SECONDARY MATERIALS

End of life recycling input rate for kaolin is estimated to be approximately 1%. This is due to the fact that many applications (ceramics, glass, refractories, cement, etc.; on the whole about 60% of total consumption) entail a thermal treatment above 400°C, during which any kaolinite group mineral is destroyed and no direct recycling is possible. In the applications where kaolin is englobed in paints, glues, rubber, plastics (and so on) no recycling is viable, because kaolinite crystals are firmly retained in the matrix. In paper recycling, different types are mixed, each having its own mineral filler and/or coating, so kaolinite occurs admixed with calcium carbonate, talc, etc and no “pure” kaolin can be recovered. Some recycling is feasible among catalysts (SCRREEN workshops, 2019).

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PROCESSING OF KAOLINITIC CLAYS

A clear distinction exists in the processing of kaolin and plastic clays (Pruett, 2006; McCuistion, 2006). Kaolin mining and processing always entail an enrichment of kaolinite group minerals through separation of other components of the raw deposit. Plastic clays are extracted by selective mining and their mineralurgical treatment is aimed at obtaining the physical status required by different end-users and it usually does not involve any separation. Therefore, plastic clays are usually processed into various forms (McCuistion, 2006): shredded (in lumps with natural humidity), mechanically dried (in lumps with a lower humidity), air-floated (in dry powder), and slurry (as water suspension ready for slip casting). In contrast, kaolin processing is technically complicated and constitutes a costly barrier for entry into many markets, where specific properties are valued, such as purity, appearance, consistency and handling characteristics (Pruett, 2006). Once raw kaolin is obtained by washing, settling and dewatering, further processing can be performed either in the wet state or in the dry state. Most kaolin employed as pigment or filler is processed by the wet route to feed the paper, rubber, plastics, paints industries, among other applications. Kaolin is typically processed in the dry state for the refractory and ceramic industries. Low grade kaolin can be sold unprocessed to cement or some ceramic manufacturers. Different kaolin categories are present on the market: airfloat, calcined, delaminated, unprocessed, and water washed. As for plastic clays, kaolin can be delivered in lumps, powder or slurry.

METAKAOLIN

Metakaolin is the material produced through the endothermic calcination of kaolin and the dehydration of $Al_2Si_2O_5(OH)_4$ phase. Dehydration process begins at 550–600 °C and continoues at a lower rate until 900 °C. It is practically completed at temperatures between 700 and 850 °C. Aiming to the decrease of the produced clinker amount globally and therefore to the decrease of CO_2 emissions by the clinker industry, metakaolin has been tested as an alternative pozzolan material. When added to a concrete mix, metakaolin accelerates the hydration of Portland cement and takes part in the pozzolanic reaction. The conditions for calcining clays in a rotary kiln differ from those needed to produce clinker. The clay needs to be fired at temperatures around 700–850 °C, approximately half of the temperature needed for clinker production (Almenares et al. 2017). Trials at industrial scale using an industrial rotary kiln (Figure 4) with a feed rate of 20 t/h, showed that kaolin can be efficiently transformed to metakaolin (Almenares et al. 2017).

Recently, metakaolin has been tested as a geopolymer component. Pilot scale tests for the synthesis of geopolymer bricks were successfully conducted using metakaolin, fly ash, and sugarcane bagasse ash. The mechanical properties and durability aspects of the geopolymer bricks were compared with the standard codes of practice for conventional burnt clay bricks, leading to satisfactory results overall (Mehmood et al. 2022).

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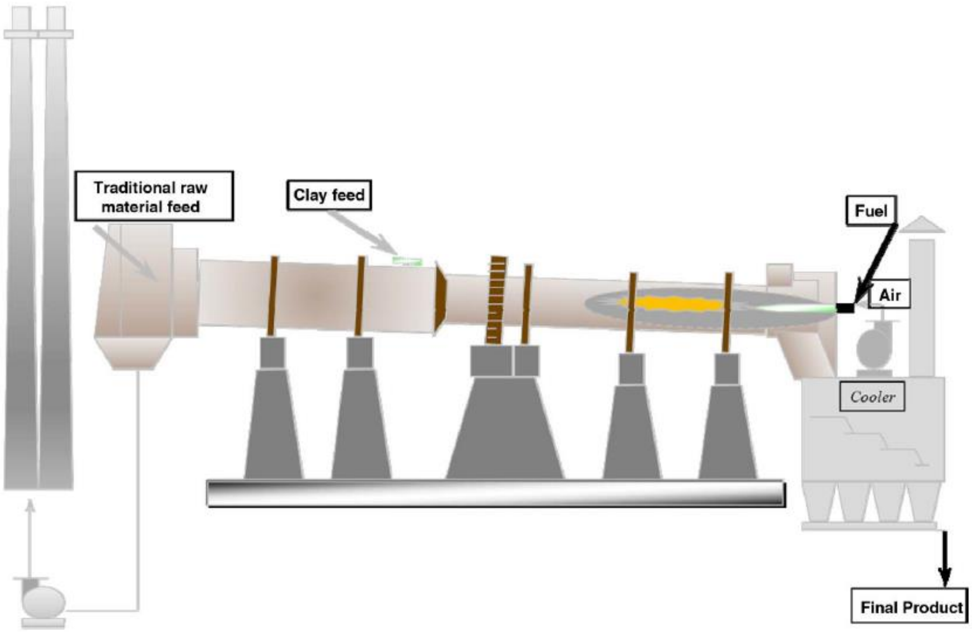

Figure 22. Industrial rotary kiln that used for the production of metakaolin (Almenares et al. 2017).

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Kaolin is one of the natural components of soil, it occurs in ambient air as floating dust and thus exposure to this substance is common but not harmful to humans. In general, kaolin's impact on human health and the environment depends on the amount and type of minerals that compose it. It is widely recognized that inhalation exposure to one of its components, quartz, causes silicosis and lung cancer. Moreover, it's been reported that a rise in exposure to quartz increases the incidence of chronic bronchitis, pulmonary emphysema, chronic obstructive pulmonary disease, autoimmune-related diseases (such as scleroderma, rheumatoid arthritis, systemic lupus erythematosus) and renal diseases (World Health Organization, 2005). Therefore, the (Occupational Exposure EU directive, 2022) sets an exposure limit of 0.1 mg/m^3 to respirable crystalline silica dust, one of the forms of quartz, for an 8-hour exposure.

The (International Agency for Research on Cancer, 2012) includes the dust of crystalline silica, the main component of kaolin, in Group 1, since it is "carcinogenic to humans". The (Classification, Packaging and Labelling EU Regulation, 2008) categorises another component of kaolin, titanium dioxide (TiO_2), as carcinogenic level 2, given that it is "suspected of causing cancer". Furthermore, the (International Agency for Research on Cancer, 2022) inserted TiO_2 in Group 2B, stating that it is "possibly carcinogenic".

Kaolin is extensively used in cosmetics and dermal exposure to this substance doesn't pose a significant threat to humans (World Health Organization, 2005). By contrast, more recent studies such as (Kawanishi, M. et al., 2020) show that "fine particles of kaolin tended to have higher genotoxic potency [over human epidermal keratinocytes and dermal fibroblasts] than coarse particles". The study contributes to scientific research by

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questioning kaolin particles' safety when used as a white cosmetic pigment and opens the way for further investigation.

ENVIRONMENTAL ISSUES

According to the (World Health Organization, 2005) kaolin has low toxicity to aquatic species and its mining doesn't pose any significant toxicological danger to the environment.

NORMATIVE REQUIREMENTS

The BMT cargo handbook provides guidelines on the transportation of aluminium silicate that forms a clay when hydrated, of which kaolin is a part of. These materials shall normally be shipped in multiple paper bags, handled carefully and to be kept absolutely dry. In terms of risk factors, dusts may be irritant to nose and throat. Suspensions of dust are a fire hazard (BMT n.a.)

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF KAOLIN FOR EXPORTING COUNTRIES

Table 11 lists the countries for which the economic value of exports of kaolin represents more than 0.1 % or more of the total value of their exports.

Table 11: Countries with the highest economic shares of kaolin exports in their total exports.

Country	Export value (USD)	Share in total exports (%)
Ukraine	66,044,836	0.1

Source: COMTRADE (2022), based on data for 2021.

Ukraine is the only country for which the value of kaolin product exports achieves 0.1 % of their total exports.

SOCIAL AND ETHICAL ASPECTS

The (Environmental Justice Atlas, 2018) reports a case of popular opposition to kaolin extraction in Portugal. Since 1965 the company SA-Mibal extracts this mineral in the city of Barqueiros (Norte region). The mining activity causes wells to dry up and craters to open in the area surrounding the quarry, triggering protests in the local community. The conflict started in 1987 and became known in the media as the "War of kaolin", when the local population strongly fought against the construction of a second kaolin mine. Clashes between strikers and the police led to the death of a 22-year-old man by an accidentally fired bullet. After several years of legal battles, in 2007 the company obtained the authorization to operate the second mine. Nonetheless, the community keeps protesting and demanding environmental and health protection.

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RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Kaolin for zeolite synthesis and application in biodiesel production

According to (Gadin, J., et al., 2022), kaolin is used to synthesise zeolites, a general term to refer to tectosilicates, which are a group of minerals constituted of alumina (AlO_4^{-5}) and silica (SiO_4^{-4}) held together by atoms of oxygen. Zeolites are characterised by high surface area, small-sized pores, and high customization of different parameters such as silica/alumina ratio, structure density and pore volume, which can be modified depending on the synthesis conditions. Doping zeolites with elements such as copper, nickel, calcium, and potassium improves its catalytic activity. Additionally, zeolite's low price, high availability, minimum environmental impact, large surface area and high porosity make them better candidates than other chemicals in catalytic applications, for example as catalysts for the transesterification of natural oils in biodiesel production. (Gadin, J., et al., 2022). (Doyle, A., et al., 2016) synthesised a zeolite Y[4] from Iraki kaolin and reported an esterification rate of the oleic acid of 85 %. This value was 9 % higher than the rate obtained with commercially available zeolites Y.

- Kaolin/ZnO composite for wastewater treatment

Zinc oxide (ZnO) is an n-type semiconductor characterized by low toxicity, high corrosion resistance and chemical stability. Given its excellent adsorption and photocatalytic properties, researchers are trying to implement ZnO nanoparticles in the wastewater treatment process. Nonetheless, some of its properties hamper its recovery from the aqueous phase, such as low surface area, rapid agglomeration, and small particle size. Immobilization and stabilization on a porous kaolin matrix is a suitable option for solving these drawbacks, adding up to the low cost and high availability of kaolin. Recently, (Mustapha, S. et al., 2020) synthesised pure kaolin and kaolin/ZnO nanocomposite, reporting that the latter had a wider surface area (31.8 m^2/g) than the former (17.0 m^2/g). The authors also compared the removal rate of chromium and iron in wastewater and the decrease of other water quality indicators (chemical oxygen demand, COD, biological oxygen demand, BOD, and chloride). The results of the study showed that the absorption rates of kaolin and kaolin/ZnO were, respectively, as follows: chromium (78 % and 100 %), iron (91% and 98 %), COD (91 % and 95 %), BOD (89 % and 94 %) and chloride (73 % and 78 %). In conclusion, kaolin can be considered a cheap and easily accessible support for the use of zinc oxide nanoparticles in wastewater treatment, allowing for high removal rates, environmental safety and recyclability.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Optimization of kaolin into metakaolin: Calcination conditions, mix design and curing temperature to develop alkali activated binder (Khaled et al 2023)

The natural kaolin deposits are inert crystalline with low calciumoxide (CaO) contents and surface area. Therefore, kaolin is not a suitable material to produce Alkali Activated Binders (AAB) due to the low strength resulting. This work aims to optimize kaolin into metakaolin and use them later as AAB.

[4] Zeolites Y belong to the family of aluminosilicate molecular sieves. They have a Si/Al atomic ratio higher than 1.5, which confers zeolite Y with higher thermal stability and catalytic activity than other types of zeolites (ACS Materials, 2019; Julbe, A. et al., 2016).

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It is found that metakaolin paste with high optimum pozzolanicity produces AAB with higher mechanical compressive strength values (20.9 MPa) after curing at 60 °C. The latter mechanical compressive strength is maximized (27.09 MPa) when metakaolin pastes are activated by 14 wt% NaOH and 10 wt% Na_2SiO_3 mixture.

- Investigation on the strength behaviours of ordinary and kaolin-modified concretes severely attacked by sulfuric acid (Twin et al 2023)

Concrete, which has an alkaline nature, is not very protective against sulphuric acid attack. Severe attacks of sulphuric acid cause the concrete infrastructures to deteriorate and result in economic losses to maintain and repair them. The aim of this research is to investigate the strength behaviours of ordinary and kaolin-modified concretes when they are severely attacked by sulphuric acid solutions with pH1, pH2, pH3, and pH4 for exposure durations of 30, 60, 90, 120, 150, and 180 days. The required tests were performed according to the American Society for Testing and Material standard procedures. The modified concretes were made by adding 5 % to 20 % kaolin by mass of cement. The Absolute Volume method was used for concrete mix design. It was observed that adding 10 % kaolin to concrete gave the maximum 28-day compressive strength among the different added percentages. It was also found that the percentage of the strength loss caused by sulphuric acid attack depends on the pH levels of the acid solutions and 10 % kaolin-modified concrete can withstand the severe attack of sulphuric acid better than ordinary concrete. Regression analyses were performed on the research data to evaluate the predicted equations for the strength loss of concrete.

- Analysis on the evolution characteristics of kaolin international trade pattern based on complex networks (Zheng et al 2022)

This study used a complex network model to analyse the global kaolin trade pattern from 2000 to 2020. The results showed that the kaolin trade between countries tends to be closer, and the trade efficiency keeps improving. The import market tends to be fragmented, which to a certain extent means that the trade voice of kaolin importers is constantly weakening. Compared with import trade, the export trade market has a greater concentration, which is inseparable from resource endowment. Developing countries, such as China and India, have gradually increased their processing capacity of kaolin, and their participation in international kaolin trade has been deepened, which is related to the increase in their industrial production capacity. China and India have gradually increased their control and counter-control over the kaolin trade.

REFERENCES

ACS Material (2019), Y-type Zeolites, https://www.acsmaterial.com/blog-detail/y-type-zeolites.html , accessed on February 2023

Almenares, R. S. Vizcaíno, L. M., Damas, S., Mathieu, A., Alujas, A., Martirena. (2017), Industrial calcination of kaolinitic clays to make reactive pozzolans. Case Studies in Construction Materials, 6, June 2017, pp. 225-232.

ATIC (2022), Australian Critical Minerals Prospectus 2022, Australian Trade and Investment Commission, available at: https://www.globalaustralia.gov.au/sites/default/files/2022-12/ATIC_Australian_Critical_Minerals_2022_9DEC22.pdf, accessed in 30-01-2023.

BGR (2022), BGR – Bundesanstalt für Geowissenschaften und Rohstoffe (2017-2021): Deutschland – Rohstoffsituation, Hannover.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958211

BMT (2023), Aluminum silicate (Kaolin), https://www.cargohandbook.com/Aluminium_Silicate, accessed on

BRGM (2020), Bureau de Recherches Geologiques et Minières.

Classification, Packaging and Labelling EU Regulation (2008), Regulation (EC) No 1272/2008, http://data.europa.eu/eli/reg/2008/1272/2022-12-17 , accessed on January 2023

CRM experts (2022), SCRREEN Experts Workshop on Platinum Group Metals. Brussels: 22.09.2022

Czech Geological Survey (2022), Mineral Commodities Survey of the Czech Republic - Czech Geological Survey, http://www.geology.cz/extranet-eng/publications/online/mineral-commodity-summaries. , accessed on

DGEG (2022), Direção Geral de Energia e Geologia., https://www.dgeg.gov.pt/pt/estatistica/geologia/minas/producao-anual/., accessed on

Dondi (2022), personal estimation by Michele Dondi of Kaolinitic clay production.

Doyle, A., et al. (2016), Biodiesel production by esterification of oleic acid over zeolite Y prepared from kaolin, http://dx.doi.org/10.1016/j.renene.2016.05.067 , accessed on February 2023

El-Aal, M. A., Said, A. E.-A. A., Abdallah, M. H., & Goda, M. N. (2022), Modified natural kaolin clay as an active, selective, and stable catalyst for methanol dehydration to dimethyl ether. In Scientific Reports (Vol. 12, Issue 1). Springer Science and Business Media LLC.

EME (2022), Ministerio para la Transición Ecológica y el Reto Demográfico - Estadística Minera de España., https://energia.gob.es/mineria/Estadistica/Paginas/Consulta.aspx., accessed on

EU occupational exposure (2004), Directive 2004/37/EC, http://data.europa.eu/eli/dir/2004/37/2022-04-05 , accessed on January 2023

Eurostat (2021), Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E), https://ec.europa.eu/eurostat/en/web/products-datasets/-/SBS_NA_IND_R2 , accessed on December 2021

Eurostat Comext (2022), Eurostat database. EU trade since 1988 by HS2-4-6 and CN8 (DS-045409). , http://epp.eurostat.ec.europa.eu/newxtweb/ , accessed on December 2022

Gadin, J. et al. (2022), A retrospect on recent research works in the preparation of zeolites catalyst from kaolin for biodiesel production, https://doi.org/10.1080/17597269.2022.2132723 , accessed on February 2023

Grand View Research (2022), Kaolin Market Size, Share & Trends Analysis Report by Application (Paper, Ceramics, Paint & Coatings, Fiber Glass, Plastic, Rubber, Cosmetics), By Region, And Segment Forecasts, 2022 – 2030, https://www.grandviewresearch.com/industry-analysis/kaolin-market, accessed on December 2022

International Agency for Research on Cancer (2012), Arsenic, metals, fibres and dust, https://publications.iarc.fr/120 , accessed on January 2023

International Agency for Research on Cancer (2022), Agents Classified by the IARC Monographs, Volumes 1–132, https://monographs.iarc.who.int/list-of-classifications/ , accessed on January 2023

Julbe, A. et al. (2016), Zeolite Y Type, https://doi.org/10.1007/978-3-662-44324-8 , accessed on February 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211

Kawanishi, M. et al. (2020), Genotoxicity of micro- and nano-particles of kaolin in human primary dermal keratinocytes and fibroblasts, https://doi.org/10.1186/s41021-020-00155-1 , accessed on January 2023

Khaled et al (2023), Optimization of kaolin into Metakaolin: Calcination Conditions, mix design and curing temperature to develop alkali activated binder, https://www.sciencedirect.com/science/article/pii/S209044792300031X, accessed on February 2023

McCuistion, J., Wilson, I. (2006), Ball clays, in Industrial Minerals and Rocks: Commodities, Markets and Uses (Kogel, J.E., Trivedi, N.C., Barker, J.M. & Krukowski, S.T., eds.). Littleton, Colorado, Society of Mining, Metallurgy and Exploration, 343-356.

Mehmood, A., Irfan-ul-Hassan, M., Yaseen, N. (2022), Role of industrial by-products and metakaolin in the development of sustainable geopolymer blends: Upscaling from laboratory-scale to pilot-scale, Journal of Building Engineering Volume, 62, 105279.

Minerals4EU (2019), European Minerals Knowledge Data Platform (EU-MKDP), www.minerals4eu.eu.

Murray, H. H. (2006), Kaolin applications. Developments in Clay Science, 2, 85-109, Elsevier.

Mustapha, S. et al. (2020), The role of kaolin and kaolin/ZnO nanoadsorbents in adsorption studies for tannery wastewater treatment, https://doi.org/10.1038/s41598-020-69808-z , accessed on February 2023

Polish Geological Institute (2022), Mineral Resources of Poland (website)., http://geoportal.pgi.gov.pl/surowce., accessed on

Pruett, R.J., Pickering, S.M.Jr. (2006), Kaolin, in Industrial Minerals and Rocks: Commodities, Markets and Uses (Kogel, J.E., Trivedi, N.C., Barker, J.M. & Krukowski, S.T., eds.). Littleton, Colorado, Society of Mining, Metallurgy and Exploration, 383-399.

SCRREEN CRM validation workshop (2019), Expert's comment, Brussels, 11 Sep. 2019.

Twin et al (2023), Investigation on the strength behaviors of ordinary and Kaolin-modified concretes severely attacked by sulfuric acid, https://www.sciencedirect.com/science/article/pii/S2214785323001669, accessed on February 2023

USGS (2018), Clay and shale, in 2015 Minerals Yearbook, Flanagan, D.M., 18 (27 pp)

USGS (2022), Mineral Commodity Summaries, https://www.usgs.gov/centers/national-minerals-information-center, accessed on December 2022

USGS (Since 2000), Mineral Commodity Summaries, U.S. Department of the Interior, U.S. Geological Survey

WA Kaolin (2020), Production of High Purity Kaolin From One of the World's Largest Resources, available at: https://wakaolin.com.au/wp-content/uploads/2022/11/5fc062bf985889f6bf35ea17_023147031.pdf, accessed in 30-01-2023.

WA Kaolin (2022), Kaolin Market, available at: https://wakaolin.com.au/kaolin-market/, accessed in January 2023

WMD (2022), World mining data, Federal Ministry of Agriculture, Regions and Tourism of Austria (Ed.): World Mining Data (since 1984).

World Health Organization (2005), BENTONITE, KAOLIN, AND SELECTED CLAY MINERALS, https://apps.who.int/iris/handle/10665/43102 , accessed on January 2023

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Zang et al (2022), Analysis on the evolution characteristics of kaolin international trade pattern based on complex networks , https://www.sciencedirect.com/science/article/abs/pii/S0301420722002318, accessed on February 2023

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